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Tactile-Sensing Techniques Applicable for Telerobots

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This document discusses the roles for tactile sensors in current and future applications for manipulanda, and reviews criteria previously used as performance benchmarks for tactile-sensing systems. It also summarizes the capabilities of existing commercial and prototype tactile sensors, and points to areas of research and development that warrant further attention.

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INTRODUCTION

Advancements in sensor transduction, signal processing, and information-extraction and analysis techniques have significantly increased the repertoire of robotic and telerobotic systems. To date, activity in robot sensor research has focused predominantly upon developing machine-vision and visual-image processing capabilities. However, experience, both in industry and the laboratory, have clearly underscored the need for comprehensive and mutually supportive sensory feedback to effectively control automata. Thus, the following concerns have prodded greater efforts for developing proximity, force/torque, and contact sensors:

- Mounting demand for improved robotic end-effector prehension and dexterity.
- Operational environments that frequently provide degraded or confusing visual stimuli.
- Limitations in the information that even the most competent vision systems can provide.

This document covers the roles for tactile sensors in current and future applications for manipulanda, and reviews criteria previously used as performance benchmarks for tactile-sensing systems. It also summarizes capabilities of existing commercial and prototype tactile sensors, and points to areas of research and development that warrant further attention.

ROLES FOR TACTILE SENSORS

Open-loop control of robotic manipulators has proven effective in industrial environs where manipulation requirements are simple; part or tool locations, geometries, and orientations are highly structured; and where objects grasped are small and robust. If manipulation tasks overtax any of these criteria, then sensors, and sometimes human operators, are used to close the control loop and provide adaptive performance capabilities. Although only a few commercial contact sensors and information-extraction strategies are available, contact, slip, and limited-pattern sensing devices are in use in the industry. In industrial settings, tactile sensors are typically used to confirm that the end effectors have contacted the objects to be grasped. The sensors also ensure proper pose and that sufficient force has been applied to grasp the object, while concomitantly avoiding excessive force that would damage either the end effector or the object grasped. In addition, the sensors enable parts or tools to seat when tolerances are small (Harmon, 1980; Harmon, 1985; Critchlow, 1985).

Simple vision, contact-switch, strain gage, and proximity sensing have been effective aids in low-order manipulator control situations. However, Bejczy (1977), has described a number of tasks that could exceed extant robotic manipulator-control capabilities. Examples of these are space station assembly and satellite servicing in orbit, extraplanetary exploration, undersea salvage and recovery operations, and even many ordinary manipulative demands faced by users of prosthetic devices. In these situations, sensory-feedback requirements for the following applications often exceed information provided by typical industrial sensors:

- Increased manipulator complexity to 6 or more degrees of freedom.
- Compliant and adaptive grasps of objects.
- Gentle, controlled, and precise transfer, assembly, or disassembly of objects encountered in demanding applications, such as prehensile and dexterous prosthetics,* autonomous robots, and telemanipulanda.

Here, use of cutaneous-like sensing of micromechanics and other physical phenomena are viewed as fundamental; that is, to effectively achieve dexterous manipulation and recognition of objects or surfaces encountered by a probing end effector (Bejczy, 1977, 1978; Coiffet, 1981; Salisbury & Craig, 1982; Overton & Williams, 1983; Overton, 1984; Cutkosky, 1985; Harmon, 1985).

Tactile or contact sensors play at least two roles in determining the capability of teleautonomous robotic system performance. First, contact sensors provide feedback information concerning the micromechanics and other stimuli associated with manipulation. This information is difficult or impossible to obtain with other types of sensors; particularly those concerned with vision. Second, simultaneous or specified tactile sensing can usefully augment vision and other forms of sensory feedback.

*Harmon (1985) estimated that approximately 375,000 disabled persons in the United States could benefit from the application of tactile-sensor technology.

Stansfield (1986) described a set of 10 tactile primitives, or tactemes,* that require direct measurement or computation from contact sensor input and that cannot be derived. Without a direct contact-sensing capability, an autonomous or teleoperated robotic system would have great difficulty in determining the following primitive—but extremely useful—characteristics of objects encountered by the end effector:

- Compliance or hardness of the object.
- Elasticity or malleability of the object.
- Surface normal or z-axis of sensor where moments about all of the Cartesian axes are zero.
- Texture or smoothness of the object's surface.
- Contact areas.
- Contact points.
- Contact edges.
- Object mass.
- Object size.
- Object temperature.

The above tactemes must be sensed directly to ascertain the composition of more complicated tactile features. These include connected edges, corners, contours, holes, etc., which enable recognition of the physical nature of the object and which are requisite for effective grasping and manipulation.

In addition to providing information about the intrinsic properties of objects, contact sensors can augment feedback provided by other sensor systems, such as vision, position, and force/torque. For example, machine-vision systems must have objects or scenes of interest lighted uniformly to successfully analyze the images obtained. The following conditions confuse machine-vision systems:

- Inadequate or nonuniform lighting.
- Shadows or specularity.
- Extraction of specific objects embedded from cluttered or complex visual backgrounds.
- Image scaling.
- Perspective distortion.

*Larcombe (1981) refers to basic tactile-sensory primitives, which can only be combined to produce tactile features, as "tactemes."

Conversely, these difficulties do not affect contact sensing. For example, it can be used to reduce noise in visual images and to test hypotheses concerning the presence and nature of the derived image; or, it can reduce image analysis time by providing nonvisual information which allows pruning of search space in object recognition tasks.

In another example, force/torque sensors placed proximal to the end effector (e.g., at the wrist) must resolve forces and torques which result from the mass, geometry, and dynamics, both of the end effector and the object grasped by the manipulator. Employing contact sensors distal to the wrist (in this example) allows one to increase the sensitivity to—and the resolution of forces and torques acting upon—the end effector, either by objects or by manipulator actuation commands.

The foregoing examples demonstrate that fusing a variety of sensor feedbacks can relax performance demands placed upon any single-sensor system. The relative importance or utility of any particular sensor type varies with the operational setting, the task requirements, and the completeness of the sensor unit. There is little doubt, however, about the efficacy of employing contact sensors in telerobotic systems in space.

PERFORMANCE CRITERIA

Initially, scientists and engineers were faced with developing devices that could provide simple and reliable contact, force, or slip sensing to aid in robotic grasping, positioning, or edge-following. Early developments could be characterized as specific engineering solutions to task-specific problems. However, the broadening demand for tactile sensors with greater sensing capabilities suggested establishing a more generalized performance criteria or developing benchmarks for the research and development community.

Efforts to develop such criteria followed principally two lines of thought. One approach was to find a consensus within the academic, industrial, and governmental research communities concerning tactile-sensing requirements for present and long-range industrial and specialized robotic systems. The other line of reasoning was to emulate natural tactile-sensing capabilities; specifically, that of human skin. Each approach served to galvanize basic research activity, and offered direction and gages of progress often necessary for gaining support.

Development of a consensus-based set of performance criteria was led by Harmon (1982). He queried a population of 55 scientists and engineers (positioned in academia, industry, and government) about tactile-sensing needs in robotic systems, and augmented responses to his questions with a summary of scientific findings to date. Given the wide ranges in the responses obtained, no statistical analyses were performed. Instead, Harmon presented summaries of remarks which were most often encountered; or which appeared to be, from his perspective, most credible and imaginative. According to Harmon's findings, an ideal tactile sensor would offer

1. Forcel or taxel resolution of 1 to 2 mm in a 50- to 200-forcel array. This recommendation was based upon a combination of concerns about matching the geometry of a human finger tip (e.g., 5 by 10 to 10 by 20 arrangements), and providing spatial resolution at the end effector ranging between 10 and 100 times the repositioning accuracy of a typical manipulator.

2. Forcel sensitivity ranging between 0.4 to 10 N with a dynamic range of 1 to 1000.

3. A wide frequency-response range between 0 and 1 kHz. High bandwidths were viewed as requisite, given the large arrays that must be scanned and the amount of information that must be processed to detect impending slip, texture, or vibration stimuli.

4. Linear response with limited or no hysteresis.

5. Joint detection of displacement, force, and thermal stimuli.

6. Easy mating of the sensor to small nonplanar surfaces, such as robotic anthropomorphic fingers.

7. Negligible power requirements.

8. Robustness in the face of potential overforce, thermal stress, humidity, radiation, corrosive environs, and resistance to abrasion.
9. Signal conditioning; and tacteme, or perhaps feature extraction, at the level of the transducer to increase processing capability and speed.
10. Limited costs to produce or to replace.

Clearly, Harmon's ideal sensor performance characteristics represent a balance between anthropomorphism and engineering pragmatism.

An alternative design goal for emulating the human somatosensory system is frequently encountered in the literature. An anthopomorphic design metric offers several benefits compared with Harmon's consensus approach. First, requirements for robotic tactile-sensing capabilities are not likely to exceed human haptic abilities. Consensus criteria will periodically have to be updated in areas where technology growth is very rapid. Contemporary investigators have already constructed prototype sensors that surpass many of Harmon's performance criteria. Second, anthropomorphic performance criteria are more objective, and less affected by one's institutional bias. Third, in many cases, tactile-sensor research is specifically directed toward emulating human skin for developing advanced prosthetics and telepresence applications. In such cases, consensus-based performance criteria are not always acceptable. Finally, directing efforts toward developing cutaneous-like tactile sensors serves to increase the numbers of investigators and diversity of expertise focusing upon construction of a most challenging model; that is, a comprehensive and unifying model of the extremely complex and perplexing behavior of the human somatosensory system. Significant improvements in robotic tactile-sensing capacity could be permitted by expanding our understanding of the human somatosensory system, particularly from the standpoint of tactile feature extraction and object or pattern recognition.

Using human skin as an engineering model is not, however, without its problems. Cutaneous receptors are embedded within a highly compliant and hysteretic medium that must balance requirements for protection, physiological control, regeneration, and other competing demands against those of haptic sensibility. These tradeoffs have produced a highly nonlinear system whose response to force and thermal stimuli varies with anatomical location, length of stimulus exposure, and spatial and temporal coincidence with previous stimuli, as well as the nature of stimulus transmission (Verrillo, 1975). Thus, one must be very specific about the site of stimulation, the stimulus paradigm used, the type of the stimulus, and the threshold criterion used when discussing human cutaneous sensor capabilities. Such limitations and difficulties in characterizing stimulus response are not easily tolerated in the engineering community. Furthermore, the debate over the number and response characteristics of cutaneous sensors is simply overwhelmed by our lack of understanding about these sensors. This includes the roles and interrelationships among cutaneous, proprioceptor, and kinesthetic sensory feedback, and the motor commands, or exploratory procedures, needed to make reliable haptic judgements and discriminations. Studies in these areas have only recently been undertaken in the psychological community (Lederman, 1982; Klatzky, Lederman, & Metzger, 1985; Klatzky, Lederman, & Bajcsy, in preparation). In summation, both sets of criteria are useful development guides for the time being, even though neither approach is ideal. For this reason, we should avoid using either set of criteria, in part or in toto, as a simple litmus test for accepting a given sensor strategem.

TECHNOLOGY STATUS

Within the past decade, substantial progress has been made in tactile-sensor technology. Commercial manufacturers now offer sensors that can provide information well beyond that of simple contact-switch, force-probe, or strain-gauge devices. A variety of devices differing in transduction methods and signal analysis requirements can be found in industry and experimental laboratories. This summary focuses upon strategies used for transducing contact stimuli and extracting information peculiar to prehensible object recognition.

TRANSDUCTION METHODS

Several methods have been proposed or developed for transducing micromechanical and other contact stimuli encountered during physical interplay between objects or surfaces and robotic end effectors. Transducers developed thus far may be classified as switch, piezo, capacitive, magnetic, or photomodulation-based devices. In the following paragraphs, each mode of transduction is briefly described; and representative examples are presented. Figure 1 summarizes the range of techniques used to transduce contact stimuli and provides graphics of representative sensor devices. Table 1 summarizes sensing capabilities reported for principal modes of transduction.

CONTACT-SWITCH DEVICES

Switch devices are typically used in manipulator applications where knowledge of a suprathreshold contact force is of principal interest. A pin or forcel, coupled to a spring, cantilever beam, or other elastic element, is physically displaced; and if forces applied are sufficient, continuity is established between a set of electrical contacts. There are a number of examples of this sensing approach. In some cases, small microswitches can be sited (Inoue, 1971) that have been used to line the surface of the robotic end effector. In others, arrays of pins have been built, which, when displaced by impacting objects or surfaces, result in contact between a conductive elastomer membrane and an underlying metal electrode (Goldgewicht, 1974).

The advantages of using traditional forms of contact switches are that they are simply designed and easily implemented. In addition, they function reliably in harsh environs, offer linear behavior with almost no hysteresis, and require minimal signal analysis. On the other hand, contact switches provide limited force information; that is, one has or has not exceeded a suprathreshold force at the switch. One also cannot gage object or surface compliance; and because of limitations in miniaturizing mechanical switch arrays, shape and texture detection is also limited. Finally, employing switch-like sensors requires the use of control models that can tolerate open-loop performance, except when switch closing or opening occurs.

Investigators at Carnegie-Mellon University and Cal Tech (Raibert & Tanner, 1982 a, b; Raibert, 1984) achieved a nontraditional and ingenious development in contact-switch technology. The latest sensor described by Raibert (1984) consists of a

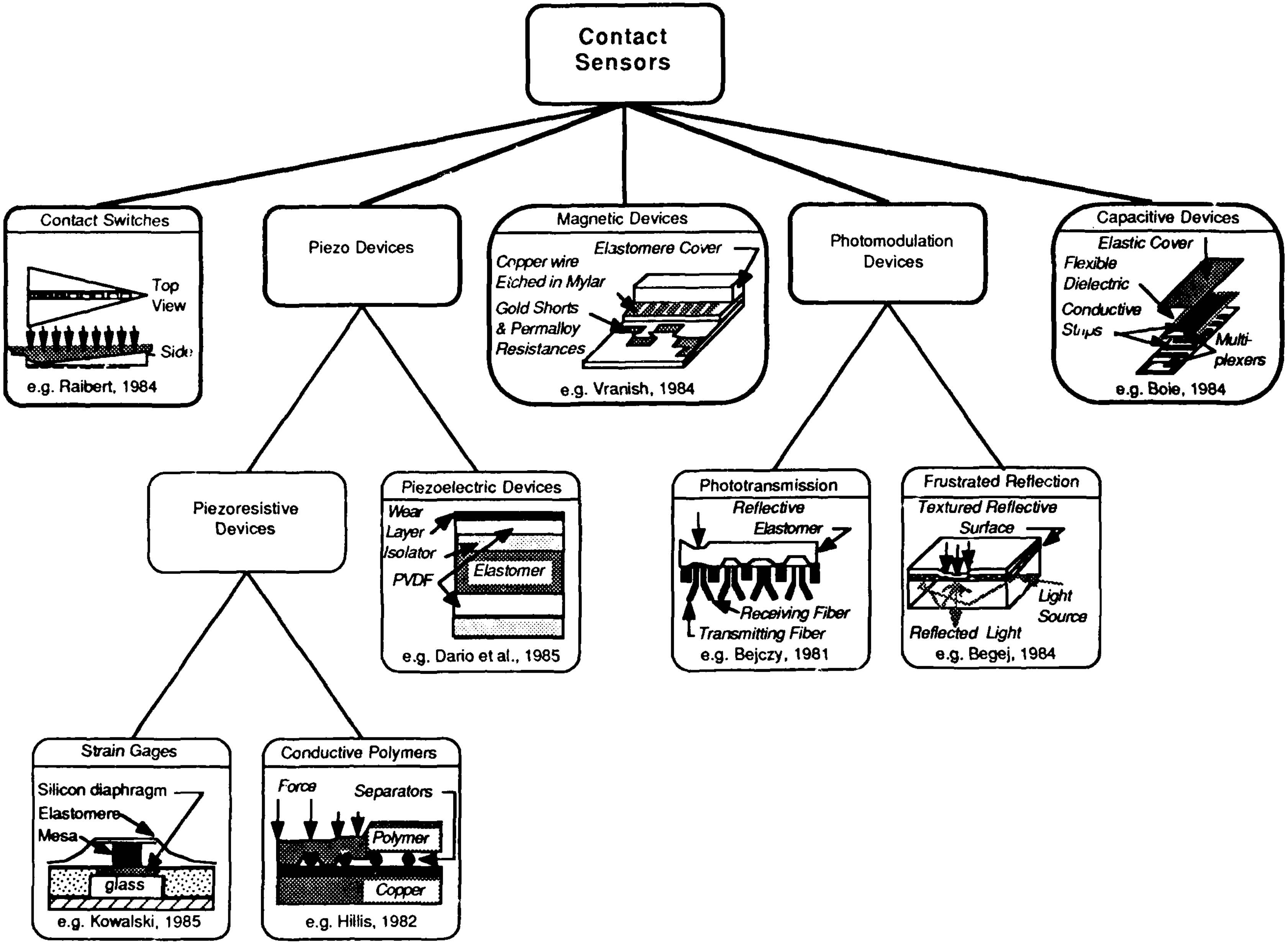

Figure 1. Technological taxonomy of contact sensors.

Table 1. Summary of capabilities of array-based tactile sensors.

BASIS OF TRANSDUCTION	DEVELOPERS	SPATIAL RESOLUTION (mm)	FREQUENCY RESPONSE (Hz)	FORCE SENSITIVITY (N)	RESPONSE RANGE (N)
IDEAL	**Harmon, Case Western**	**1.0**	**1000**	**0.01**	**0.01-9.81**
PHOTOMODULATION	Lord Corporation Schneiter and Sheridan, MIT Tactile Robotic Systems	0.6-2.5	12-333	0.0004-0.03	0.1-6.68
PIEZOELECTRIC	Dario et al., University of Pisa University of Florida	0.3-3	100	0.20	0.20-784.80
PIEZORESISTANCE	Hillis, MIT Purbrick, MIT Transensory Devices Inc. Barry Wright Corp.	0.6-2.0	30-40	0.05-2.26	0.5-490.0
CAPACITIVE	Siegal et al., MIT	1.9	-	0.02	2.00

Adapted and modified from Pennywitt, 1986.

conductive elastic layer that overlies a VLSI chip in which an array of tapered notches are carved into the silicon dioxide overglass. Pressure applied to the wear surface causes the conductive elastomer to protrude into the cavity and contact one or more of the metallic electrodes arranged in a linear grid at the bottom of the notch. As force levels are increased, the elastomer continues to protrude up through the narrowing notch and incrementally and sequentially contact the metal electrodes aligned in a linear grid upon the base of the notch. Thus, the grid of electrodes mechanically converts the force inputs from analog to digital form. Along with economizing upon digitization circuitry, the investigators have taken advantage of VLSI techniques to permit local and parallel processing of digital representations of forces. Force response characteristics can also be modified by (1) selecting an elastomer with the desired modulus of elasticity or (2) varying the geometry or size of either the notch in the overglass or electrode grid. Overall, this design is quite attractive to applications employed as follows:

- For minimizing central processing capabilities and power requirements.
- For intermingling a composite of incremental forcel sensitivities within a sensor surface.
- Where surfaces for sensor mounting are fairly planar.
- Where risks of significant overforce or strong electrical fields are low.
- Where low cost is not a firm requirement.

PIEZO-BASED DEVICES

Many piezo-based contact sensors have been used, because subjecting them to mechanical or thermal stress causes changes to occur in the electrical properties of the material comprising them. In some materials, stress produces changes in electrical resistivity, while in others, stress generates small transient electrical currents.

Piezoresistive Devices

Metals, silicon, and several conductive materials have demonstrated piezoresistive effects; that is, changes in electrical resistance when subjected to mechanical stress. This class of contact sensor, often referred to as strain gages, generally exhibits good sensitivity and response linearity, limited hysteresis, favorable signal-to-noise ratios and response stability, and good frequency response. However, piezoresistive devices typically offer limited spatial resolution of forces and are relatively expensive. Exceptions to this are piezoresistive polymers that offer pliable conformable arrays at the expense of signal hysteresis and poor durability.

Metal strain gages, consisting of metallic conductors (e.g., wire or metal foil) bonded to beams or other objects of interest, have been used for several years to measure strain produced in response to force, torque, pressure, displacement, or acceleration stimuli. Distorting the structure and the gage provokes a positive or negative shift in gage resistance. Metal strain gages are reliable and fairly linear in operation; they exhibit limited hysteresis and can resolve a force/torque system in three space, if rosettes of gages are properly positioned about the structure (Critchlow, 1985).

Metal strain gages are also susceptible to noise or drift when exposed to other physicial stimuli (e.g., temperature shifts and corrosion). Some extraneous stimuli, such as thermal drift, can be offset by adding a compensating gage into the bridge circuit and exposing the gage to all but the mechanical stimuli.

Silicon strain gages are based upon the same principle as metal gages, but offer some advantages. Higher gage factors found with silicon devices permit increased force sensitivity. Silicon allows considerable miniaturization and forcels to be densely packaged without encountering significant problems with electromechanical connectors. It also permits placement of processing circuitry on the same chip as the piezoelement.

However, silicon does have drawbacks. It can be stiff, fragile, and not mount well on nonplanar surfaces. Forcels can be micromachined to obtain flexibility, but at the expense of sensitivity (Kowalski, 1985). To ensure adequate end-effector friction, sensors also have to be covered with a compliant elastomer wear surface that can introduce hysteretic behavior.

An example of a strain gage application can be found with Peruchon's dynamic touch probe which is sensitive to both static (position detection) and dynamic (force detection) stimuli (Peruchon, 1979; cited in Coiffet, 1981). A rod-like probe (3 mm in diameter by 12 cm long) contacts the object and transmits forces to the central part of a flexible, cross-shaped blade. This blade is equipped with three gage bridges that detect the normal force component of the pressure and the moments about the x and y axes. A computer or a person moves the probe about the object of interest and continuously records forces and moments in Cartesian space to produce scan contours of the object or surface explored. An ingenious extension of this design can be found in the bonding of eight pairs of gages upon a Maltese-cross structure mounted within the most distal digit of a robotic hand (Brock & Chiv, 1985).

To overcome some of the fabrication limitations encountered with metal and silicon gages and to improve spatial resolution of contact pressures, some investigators have experimented with *piezoresistive polymers and carbon fiber felts* (Larcombe, 1981). Though the number of materials which exhibit piezoresistive properties are limited, the materials are inexpensive, tolerate wide ranges in temperatures, and permit construction of conformable arrays of forcels. The main disadvantages encountered are that piezoresistive-polymer materials are often noisy and frequently exhibit nonlinear and hysteretic responses; in addition, they are highly susceptible to drift and often fatigue at unacceptable rates with repeated use.

Purbrick (1981) developed a conductive silicon-rubber array in which both row and column electrodes are made of conductive silicon rubber. Row and column elements are lengths of rubber, formed convexly to minimize the contact area between electrodes and also reduce the resistance to current flow between electrodes in the unstressed state. When force is applied, these rubber electrodes are deformed, and the area of contact increases; this results in a logarithmic decline in electrical resistance. The design offers good force sensitivity and pressure resolution using sequential scanning techniques. It is inexpensive and can withstand large force overloads. Aside from the operational limitations of using a conductive elastomer, Purbrick reported nontrivial drift in the baseline signal after 5 minutes of usage.

Hillis (1982) built a 1 cm^2 16 by 16 array using an ansiotropic conductive elastomer laid upon an intervening separator and subsequently a circuit board etched orthogonally to the elastomer's direction of conduction. The separator isolated the conductive polymer from the printed circuit (PC) board when contact forces were removed. As contact force was applied to the wear surface, the conductive elastomer protruded through the separator material and contacted the PC board. Force magnitudes were correlated with the contact area, and, ultimately, current flow between the elastomer and underlying electrode surface(s). Both force sensitivity and response range were found to depend highly upon the properties of the separator material. For example, large force ranges were obtained with a sheet of nylon stocking serving as the separator. On the other hand, limited response range, but high sensitivity, was obtained when the separator consisted of nonconductive paint particles sprayed between the elastomer and PC board. These devices are reported to be rugged and to tolerate overforces; however, force response curves obtained showed nonlinear behavior.

Overton and Williams (1983) developed a sensor using an 8 by 16 array of hair-pin loops of conductive silicone rubber embedded within a thin (25 by 25 by 8 mm) silicon rubber cube. Each forcel could reliably respond to a 10 percent of full-scale (0 to 8.8 N) loop deformation force. The entire array could be sequentially scanned at a rate of 44 Hz.

Development efforts with conductive elastomers now have progressed to the point that a commercial sensor has been developed. The Barry Wright Corporation markets a proprietary conductive polymer 16 by 16 array claimed to possess limited hysteresis. By sequentially scanning the 4 cm^2 matrix at 30 Hz, one can obtain a 1:256 dynamic range with spatial resolution up to 1.3 mm.

In search of a more robust conductive piezoresistive material, Larcombe (1981) has used a filamental form of carbon woven into felt. The carbon-filter felt is very robust and possesses a large dynamic range. Yet, like conductive polymers, the material can be easily formed about a variety of end-effector geometries. Larcombe has constructed a matrix of felt strips placed across one another to produce multistrip junctions that spatially resolve applied force. Compressing the fibers reduced resistances of felt strips that were sequentially scanned to determine force distribution.

Piezoelectric Devices

In certain materials, mechanical deformation or thermal absorption produces electrical polarization and generates transient electric fields. The electrical charges produced are short lived and decay with a time constant determined by (1) the material's dielectric constant, (2) internal resistance, and (3) the input impedance of the electronic interface to the material. Recent advancements in materials have produced pliable piezoelectric films, such as polyvinylidene fluoride (PVDF), which is rugged enough to withstand 120°C, thousands of volts, and millions of Gs before its piezoeffects are destroyed (Chatigny, 1984). These properties have interested investigators pursuing "artificial skins" for use in prosthetic and robotic-tactile sensing applications.

Sensors based upon the ferroelectric* properties of PVDF are best exemplified by the work of Dario and his colleagues at the University of Pisa (Dario, P., De Rossi, D., Domenici, C., & Francesconi, R., 1984; Dario, P. & De Rossi, D., 1985). Studies of the basic properties of PVDF (and use of human skin as a development model) have led Dario and coworkers to develop a composite ferroelectric and conductive polymer tactile sensor; this sensor is capable of transducing both mechanical and thermal stimuli. It consists of a formed PC board containing an 8 by 16 array of metal electrodes on 3-mm centers. A thick sheet of PVDF film is bonded to the PC board to capacitively transfer its electrical activity to the electrode array. To measure static force, a sheet of pressure-sensitive, conductive silicone rubber is laid upon the PVDF film (called the "dermal" layer). Finally, a thin layer of metal-coated PVDF film is used to cover and shield the conductive rubber layer. The outer layer of PVDF film is called the "epidermal" layer and is used to detect very small pressure variations or vibrations required for texture analysis.

To evaluate thermal characteristics of objects, a thin layer of flexible, resistive metallic paint was applied to the back of the "epidermal" layer of PVDF; and a dc power supply regulated its temperature at 37°C. Heat flow occurring between the PVDF film and object contacted (determined by the thermal properties of the object) was to be estimated by comparing differences in electrical activity between the outer and inner PVDF layers. (These layers are somewhat thermally isolated by the intervening layer of silicone rubber.)

Dario et al. (1985) argued that the sensor could perform the following functions:

- Sense fine contacts, as well as vibrations experienced while exploring textured surfaces or when objects slip along the sensor's outer layer of PVDF.
- Detect solid geometric and mechanical properties of objects by conveying differential pressures to densely packed electrode arrays beneath the inner PVDF sheet.
- Detect differences in the thermal properties of objects contacted by differential pyroelectric response between outer and inner layers of PVDF.
- Sense static force by changes in the resistance in the compressed conductive elastomer.

An alternative to using conductive elastomers for monitoring static force, or pressure, was to rely upon ultrasonic time of flight measurements (Dario et al., 1985). An inner layer of PVDF would be excited, transmitting ultrasonic pulses to the outer PVDF layer. Time of flight through the elastomer would be related directly to the extent of elastomer distortion.

Battelle Labs has also developed such a sensor using arrays of shaped conductors upon an excited layer of PVDF film segregated into forcels. Excellent force-resolution capabilities for selected driving frequencies and spatial resolution of force

*Ferroelectric materials generate electric charges in response to either mechanical or thermal stress.

stimuli were obtained by sequentially energizing the forcels in the transmitter array and recording the time of flight in the receiving PVDF film. (This is the film that lies between an elastic separator and an elastic wear surface.)

CAPACITIVE DEVICES

Capacitance-based contact sensors rely upon changes in the impedance to ac-current flow through an elastic dielectric material sandwiched between parallel conductors. Impedance is reduced when contact forces reduce the separation between plates. Several tactile sensors have been developed using this strategy (Boie, 1984; Chun & Wise, 1985; Siegal, Garabieta, & Hollerbach, 1986).

One example of a capacitive sensor is provided by Boie (1984) who described an array of capacitors composed from a flexible three-layer sandwich. Flexible PC boards with electrode strips running orthogonally to one another comprised the top and bottom layers with an intervening elastic dielectric layer placed between the boards. Capacitor elements were formed at those locations where strips overlapped. An 8- by 8-forcel array with an active area measuring 2.5 cm^2 allowed sampling rates of 390 Hz. Disadvantages of this sensor design were (1) only normal forces were detectable, (2) the top electrode strips were susceptible to puncturing, (3) susceptibility to electrical interference was high, and (4) problems with mechanical and electrical crosstalk had not been eliminated.

A more flexible 8 by 8 capacitive tactile array with 1.9-mm taxel spacing was built later by Siegal, Garabieta, and Hollerbach (1986). Force-response characteristics of the sensor revealed that large linear regions existed in spite of hysteresis. To provide a thermal-sensing capability to aid in recognizing objects, the array was augmented with a 4 by 4 thermal-sensing thermistor array and heating layer. Objects possessing different thermal coefficients can be differentiated by monitoring the thermal-decay profile upon contacting the object.

Capacitive-based sensors offer (1) good sensitivity and spatial resolution of force; (2) high frequency response; (3) the potential for forming around complex geometries, such as a finger-like end effector; and (4) good signal-to-noise ratios in certain environments. The main disadvantage of these devices is their susceptibility to drift and poor signal-to-noise ratios when exposed to electrical fields commonly found in manufacturing areas (Critchlow, 1985).

MAGNETIC DEVICES

Because of the variety of magnetic-ranging or proximity sensors available in the commercial market, there are recommendations for developing magnetic-based contact-sensing systems. Recent design proposals have relied upon magnetoresistance, magnetoinductance, and the Hall effect to sense normal, and in some cases, shear forces. When subjected to changes in magnetic-field strength, magnetoresistance devices produce changes in electrical conductivity, magnetoinductive devices produce electric fields, and Hall-effect devices produce differences in charges between opposite sides of a semiconductor supplied with current.

Hackwood, Geni, and Nelson (1983) described a magnetoresistive sensor consisting of an array of magnetic dipoles embedded within an elastomer. Deformation of the elastomer resulted in displacing and changing the relative position of the magnetic dipoles when compared with permalloy magnetoresistor pickups. The electrical output from the magnetoresistor element varies with changes in magnetic field strength resulting from repositioning the dipole. Assuming the magnetic dipole behaves like a zero-radius rod, appropriate placement of magnetoresistors could detect 5 degrees-of-freedom, translation, shear, and normal torque.

Vranish (1984) proposed a magnetoinductive approach for detecting normal forces applied to a thin elastomer. Within the elastomer was a dense matrix of wires carrying an ac current. Displacements of the "metallic glass" overlying small transformers were proposed to sense induced magnetic fields. Vranish felt that such a device could be used as an imaging skin with forcel separations of 0.5 mm and forcel sensitivities as low as 0.1 N, with a 9-bit dynamic range.

The Hall effect offers another method for measuring contact forces. Sensors may be designed so that contact forces displace Hall cell(s) toward the magnetic field. Force, or displacement, is calibrated against the change in potential produced when the current-carrying semiconductor is immersed farther into the magnetic field (Kinoshita, Ohishi, & Yoshida, 1983; Critchlow, 1985).

Magnetic-based contact sensors have only recently been considered as candidates for contact sensors and, thus, require further refinement. However, significant design and development problems exist. For example, the gage factor for normal forces is far less than that for shear or torque stimuli in Hackwood et al.'s (1983) magnetoresistive device. Shear-force information is important, but not at the expense of normal force sensitivity. Magnetic-based devices are also very susceptible to noise from magnetic or electric fields, which are frequently encountered in robotic applications outside the laboratory. Finally, fabrication into flexible nonplanar surfaces can be difficult and costly.

PHOTOMODULATION DEVICES

Photomodulation techniques offer response sensitivity and spatial resolution of force patterns which are difficult to match by other transduction methods. The transduction scheme is essentially unaffected by the presence of electromagnetic fields, and offers the potential for detecting and measuring shear forces. For these reasons, photomodulation transduction methods are being developed at industrial and basic research institutions (Betts, Duckworth, & Austin, 1980; Bejczy, 1981; Rebman & Trull, 1983; Schneiter & Sheridan, 1984; Tanie, Komomya, Kaneko, Tachi, & Fugikawa, 1984; Mott, Lee, & Nicholls, 1984; Begej, 1984, 1985; White & King, 1985; Schoenwald, 1987*). Development activities have focused upon either modulation of phototransmission or frustration of internal reflection.

Two photomodulation techniques are presently being used. The first method disrupts light transmission at photo-optical junctions. Devices currently marketed by the Lord Corporation rely upon displacing a pin, attached to an elastic element, which shades and can ultimately occlude light transmission between pairs of phototransmitters and receivers. Another commercially available sensor, produced by Tactile Robotic Systems, measures the degree of disruption of phototransmission across a

*Personal communication.

fiber-optic junction which is misaligned when the forcel is displaced. Disruption of phototransmission is proportional to the force experienced (Hill & Sword, 1973; Rebman & Trull, 1983).

An alternative photomodulation technique is currently under development at Rockwell International (Schoenwala, Thiele, & Gjellum, in preparation). The sensor consists of eight optical fibers arranged in an equispaced linear-array matrix of sensor sites created by a row and column arrangement of fibers. The rows are separated from the columns by either a transparent or opaque elastomer with light-transmission channels drilled at row/column junctions to permit direct optical coupling. Forces applied to a wear surface compress the elastomer and increase phototransmission by decreasing the transmission distance at junctions. Optical fiber surfaces were abraded at the points of intersection to enhance coupling light radiation from one fiber to the other. Normally, no light would radiate from the fibers for the kind of lateral deformation experienced in this design. Fibers in one array are sequentially excited by light-emitting diodes. Fibers in the receiving array are completely scanned during the time interval that a single transmitter fiber is excited; and receiver fibers are connected to photodiodes, which are sequentially scanned to detect differences in phototransmission.

To achieve greater spatial resolution of contact forces, some investigators have developed methods to characterize the degree and pattern of displaced elastic membranes. Bejczy (1981) attached 16 pairs of fiber optic cables—one fiber serving as the phototransmitter, the other as a receiver—to a transparent elastic membrane that possessed a reflective wear layer. Forces applied to the membrane distorted the reflective surface and reflected the light away from the receiving fiber. Reflected light was captured by receiving optical fibers and transmitted to a photodiode matrix for recording and analysis. Later, Schneiter and Sheridan (1984) economized the design by treating each optical fiber as a phototransceiver and then densely packing the membrane with additional fibers. Spatial resolution was increased significantly to 0.6 mm betweeen fiber optic array elements which were scanned using a television camera.

In another strategy, light is transmitted into the side of a transparent plate. A textured reflective elastic membrane is placed on one side of the plate, and a photoreceiving device is attached to the other side. The remaining surfaces are reflective. Forces applied to the membrane result in sections of the membrane contacting the surface of the plate and then reflecting light directly across to the photoreceiver. The principal difference between devices among investigators was the method used to record reflected light. Tanie, Komomya, Kaneko, Tachi, and Fugikawa (1984) used a photodiode array to record light patterns and intensities, while Mott, Lee, and Nicholls (1984) used a solid-state camera. Begej (1984, 1985) relayed visual patterns, via fiber optic cables, to a remote camera to aid in miniaturizing end effectors. In general, these sensors all performed superbly. Variations in performance were caused by the elastomer's texture, its modulus of elasticity, and the resolution and sensitivity of the photoreceiver.

In summary, both techniques of photomodulation and frustration of internal reflection offer good response sensitivity, excellent spatial resolution of forces, tolerance of electromagnetic fields, and the potential for detecting and measuring shear forces (White & King, 1985). The present drawbacks with photomodulation devices are that densely packed fiber optic arrays often do not tolerate prolonged usage or abrasion; and the large number of optical fibers, along with the photodetection devices, is difficult to accommodate when mounting the device upon small nonplanar structures.

INFORMATION EXTRACTION

Until recent years, tactile sensors were crude; and force stimuli were recorded as either binary suprathreshold inputs for confirming contact, or as calibrated analog or digital signals used to measure and control gripper forces through servosystems. Rudimentary estimates of object boundaries could be derived from end-effector postures recorded during successive controlled grasping movements. However, these data offered little difficulty during signal recording, processing, or interpretation. Thus, there was little development of techniques for analyzing tactile information until the arrival of array-based sensors, which provided information beyond that of normal force (e.g., shear, torque, thermal, and texture).

In some respects, tactile images pose fewer difficulties in extracting information from sensor records. The tactile image is local and, thus, is not cluttered with extraneous background stimuli. The image obtained can be relatively noise-free, and many existing visual-image processing and interpretation techniques (e.g., thresholding, filtering, and mask or template analysis and matching) can be used to evaluate the tactile image. Finally, many of the tactile primitives described by Stansfield (1986) can be extracted easily and quickly without significant computational demand, and can be used directly for pruning search space and in probabilistic evaluation of remaining candidate objects.

However, difficulties are encountered when analyzing tactile images. The mechanical contact required with the object of interest can distort its form and present deceptive images. In addition, sometimes visual-image processing algorithms fail when applied to tactile-imaging problems. For example, Ellis (1986) describes analytical failures with tactile imprints of textured surfaces when visual-imaging techniques were employed for texture characterization. Failures were attributed to limitations in the density of step discontinuities and to poorer step localization typically encountered with tactile images. Finally, a most difficult problem lies in scheduling and controlling tactile-sensor contacts or movements about the object (Schneiter, 1986). As previously noted, the tactile sensor is often smaller than the object of interest, providing only a limited sensory experience in any given grasp. Repeated contact is required for object recognition. Although the goal is clear—to obtain only as much information as is needed to identify the object in as few movements as possible—a generalizable strategem has yet to be devised.

Developments in tactile image analysis strategies should be considered in their initial stages. Candidates for tactile primitives and hierarchies to be used for deriving more complex haptic features are being proposed (Stansfield, 1986). Psychological studies have also begun (1) for finding procedures used by humans in haptic exploration and discrimination of the object's "form, substance, and function" (Lederman, 1982; Klatzky, Lederman, & Metzger, 1985) and (2) to establish corollaries useful in the robotic domain (Bajcsy, Lederman, & Klatzky, in press).

CONCLUDING REMARKS

Impressive developments in contact-force transduction have occurred over the past decade. A few experimental devices have demonstrated sensing capabilities exceeding several criteria, which, a few years ago, Harmon (1985) viewed as ideal. However, significant development hurdles still must be overcome in transduction and extraction of information from tactile-sensor inputs.

From the standpoint of transduction, further efforts must be made to (1) detect and measure shear and torque forces at the surface of the sensor; (2) find or develop flexible materials with low hysteresis and limited fatigability for use in constructing and protecting sensors; and (3) improve packaging systems for sensors mated to dexterous anthropomorphic end effectors operating in space, deeply at sea, and in other harsh environs. Presently, the few sensors that provide some form of shear or torque information do so at the expense of device compactness and normal force sensitivity; or they require relatively clean operating environs to prevent the mechanical slip-sensing elements from clogging (Harmon, 1985).

New materials must be found or developed to improve linearity and the range of sensor response and flexibility, while at the same time increasing material robustness and the tolerance of inevitable abrasion encountered with robotic manipulation. All high-performance transducers developed thus far face these problems.

At this point, greater thought must also be given to packaging sensors. Prototype transducers which offer excellent force sensitivity and spatial resolution are difficult to integrate (1) into relatively small dexterous anthropomorphic end effectors or (2) aboard autonomous mobile robots which must economize both on size and energy demands. Furthermore, packaging schemes must anticipate the need for frequent replacement; particularly, when robots are placed in operating environs where access is difficult due to distance or because of biohazards. Damage to tactile-sensing elements placed upon robotic end effectors is inevitable; and robust processing algorithms, or human operators, will probably not function well when large numbers of forcels are damaged and not replaced nor repaired.

The most significant difficulty facing development and application of future tactile sensors is the lack of a grammar for haptic sensing. Present sensor capabilities allow detection and recording of many primitives believed to underlie the haptic sense. These primitives must be assembled and combined with other sensor data (e.g., posture, kinesthesia, and vision) to permit discriminating touch and to sufficiently characterize, in real time, the essential micromechanics of manipulation. Present algorithms are efficient only for simple manipulation tasks or when using a highly constrained search space for identifying an object. Increasing the difficulty of object identification, or relying upon multiple tactual cues to complete complex manipulations, demands human intervention. Presently, only such intervention can fuse, selectively filter sensor information, construct and test percepts, and plan and execute control over manipulators. Until a valid haptic model and an hierarchical control schema are developed, the following requisite actions will be difficult to accomplish:

1. Ensuring that transducers are properly designed for acquiring needed touch features.

2. Guiding decisions concerning end-effector geometry and spatial organization of sensors.

3. Optimizing data acquisition procedures from the standpoints of both information extraction and timeliness in executing probing and grasping movements.

4. Optimizing construction and traversal of object search space.

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